Selecting an optimal tool sequence for 2.5D pocket machining while considering tool holder collisions

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Abstract Milling using a sequence of tools has become very attractive with the advent of rapid tool change mechanisms in modern CNC machines. However, the commercial CAM systems used to generate G&M code rely on experienced process planners to select a good tool sequence. When a tool sequence is selected and tool paths are generated, NC-verify systems are used to check the tool paths for tool holder collisions. If tool holder collisions are detected, the part has to be re-planned ab-initio. In this paper, we describe a method to select an optimal tool sequence by formulating the problem under certain assumptions as the shortest path solution to a single source directed acyclic graph. Also described is a method to incorporate tool holder solution in the context of selecting an optimal tool sequence. Examples have been worked out to illustrate the workings of the algorithm.

Keywords 2.5-Axis machining · Tool sequence selection · Process-planning

Nomenclature

\[ f(p, h) \] Removal volume represented by a planar bottom face \( p \) and a depth \( h \)

\[ t_m \] End milling cutter with diameter \( d_m \) and length \( l_m \)

\[ A_m(f) \] Nominal accessible area of a tool \( t_m \) within the face \( p \) of feature \( f \) without taking into account tool holder.

\[ D_{mn}(f) \] Clean up or decomposed area of a tool \( t_n \) without considering the tool holder within the face \( p \) of feature \( f \) after the larger tool \( t_m \) has machined to the extent of \( A_m(f) \)

\[ A'_m(f) \] Accessible area of a tool \( t_m \) within the face \( p \) of feature \( f \) while considering tool holders

\[ D'_{mn}(f) \] Decomposed area of a tool \( t_m \) within the face \( p \) of feature \( f \) while considering tool holders

\[ \text{Offset}(p, d) \] Function to create a planar offset of a face \( p \) through a signed distance \( d \)

Introduction

Process planning for milling consists of three main tasks. The first identifies removal volumes/machining features and various access directions for machining them (Gao & Shah, 1998; Regli, 1995). The second clusters them into setups based on the feasibility of machining these removal volumes in a particular direction and clamping the stock (Echave & Shah, 1999; Kannan & Wright, 2001). The final task consists of selecting appropriate tool sequences.

Current state of the art process planning systems (SURFCAM, 2002; MASTERCAM, 2002) allow users to select two or more tools for machining the pockets. The actual tool sequence selection is left to the human process planner. The process of time or cost optimization is one of trial and error where complete process planning has to be done in order to validate the plan and calculate costs using NC-Verify systems. Tool holder collision is another serious issue. NC-verify systems can be used to detect tool holder collisions. If tool holder collisions are detected, the only solution is to eliminate the offending tools and re-plan ab-initio.
The issue of selecting tool sequences has been addressed by several researchers (Arya, Cheng, & Mount, 1991; Bala & Chang, 1991; Chen, Lee, & Fang, 1998; Joo & Cho, 1999; Kunwoo, Kim, & Hong, 1994; Lee & Chang, 1995; Lim, Corny, Ritchie, & Clark, 2000; Veeramani & Gau, 1997; Yao, Gupta, & Nau, 2001). However, none of these researchers have incorporated tool holder collision handling in their algorithms.

In this paper, a systematic method has been developed to select an optimal tool sequence. The problem of selecting an optimal tool sequence has been formulated as the shortest path solution to a single-source, single-sink directed acyclic graph under certain assumptions. The nodes in the graph represent the shape of the removal volume after the tool in the node is done machining to the extent of its accessible area at each depth of cut. The edges represent the cost of machining. Methods have been described to find accessible areas in presence of stock boundary open-edges, and finding decomposed sub-pockets. Re-interpretation of the assumption used in the formulation of the problem results in an elegant method to handle tool holder collisions.

Problem statement

The objective of this research is to find the cheapest tool sequence \( T_{\text{opt}} \) to machine a feature/pocket \( f(p, h) \) given a candidate set of tools \( T = \{t_1, t_2, \ldots, t_n\} \) with diameters \( d_1 > d_2 \cdots > d_n \). Also given is the intermediate stock \( I \). The cheapest tool sequence must be such that no tool \( t_m \in T_{\text{opt}} \) causes tool holder collision with the intermediate stock while machining the region assigned to it.

Tool sequence selection formulation

In this section, we present the basic graph algorithm formulation of the tool sequence selection problem. The material presented is reproduced from an earlier publication by the author (D’Souza, Wright, & Séquin, 2001) for the sake of completeness.

Given a set of cutting tools and a 2.5D feature, the first step in tool sequence selection is the determination of the region that each tool can machine in the feature without gouging. This region is represented as an area called accessible area that the tool will traverse at every depth of cut in the pocket. The next step is the determination of feature decomposition. Given two tools of different diameters, the decomposed area is the area that the smaller tool traverses at each depth of cut for clean up machining after the larger tool is done machining whatever it can reach in the pocket. Given the accessible areas of various tools, and the decomposed areas of all possible tool pairs, the problem of selecting the optimal tool sequence is then formulated as the shortest path search in a single source, single sink, directed acyclic graph.

Accessible area

Accessible area \( A_m(f) \) in feature \( f \) for a tool \( t_m \) is defined as the area within the pocket face \( p \) that the tool can reach without gouging. This is the area that the tool traverses over the area \( A_m(f) = \text{Offset}(X, 0.5d_m) \). Figure 1 illustrates an example. Note that even though the tool traverses over the area \( A_m(f) \), the material removal within the feature is only to the extent of \( A_m(f) \cap p \).

Algorithm 1: Accessible Area calculation without considering tool holder collisions

PROCEDURE ACCESSIBLE_AREA \( (f, t_m, I) \)

\[
U \leftarrow \text{section of } I \text{ at the level of } p \\
V \leftarrow U - p \\
W \leftarrow \text{Offset}(V, 0.5d_m) \\
X \leftarrow p - W \\
\text{if } (X == NULL) \# \text{ tool cannot enter} \\
\quad p \text{ without gouging } \#/
\]

\[
A_m(f) \leftarrow NULL \\
\text{else} \\
A_m(f) \leftarrow \text{Offset}(X, 0.5d_m) \\
\text{endif}
\]

An important property of the accessible areas results from the fact that tools of smaller diameter can reach a larger area in the pocket as compared to tools of larger diameter. In other words,